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EVALUATION OF TRAINED VISIBLE EMISSION OBSERVERS FOR FUGITIVE EMISSION OPACITY MEASUREMENT

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16. ABSTRACT

A smoke generator was modified to emit white or black smoke in a horizontal direction near ground-level to simulate fugitive emissions. Observers were placed at a slightly higher elevation than the smoke generator and were then shown smoke plumes at four different opacity values against a dark terrestrial background. They read the opacities of the smoke and recorded their observations. The observers also evaluated smoke plumes from a conventional vertical emitting smoke generator under the same clear sky lighting conditions to determine that the observers had no bias when viewing normal plumes.

For the white smoke, the observer's opacity readings of the simulated fugitive emission plumes were not significantly different than the opacity readings of the conventional plumes for opacities around 15-20%. Above 20% opacity, the observer readings of the white fugitive plumes become increasingly lower than the vertical plume readings. At 40% opacity, they were lower on average by about 8% opacity. For the black smoke, the observer readings of the simulated fugitive plumes were lower at all opacity levels. At 15% opacity, they were on average lower by about 5% opacity, and at 40% opacity, they were lower by about 11% opacity. For both white and black simulated fugitive emission plumes, the observers sensitivity to changes in opacity levels declined relative to the conventional verticle stack plumes.

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ABSTRACT

The stack of a visible emission training school smoke generator was modified to emit white or black smoke in a horizontal direction near ground-level to simulate fugitive emissions. Trained smoke observers measured the opacity of these simulated fugitive emissions against a dark terrestrial background and under clear sky lighting conditions. They measured both white and black emissions generated at four different opacities -- 15, 20, 30 and 40%. The observers also measured the same opacity of smoke plumes emitted from an unmodified training school smoke generator. These vertical-flow smokestack plumes were evaluated against a sky background to provide reference data on the observers ability to measure the opacity of conventional stack plumes under the same clear sky lighting conditions used for the fugitive plume tests.

The observers measured opacities of white fugitive emissions with accuracies similar to the conventional stack emissions when opacities were in the range of 15 to 20%. As opacity increased, however, the observers increasingly underestimated opacity. At 40% opacity, observer measurements were lower on average by about 8% opacity. The opacities of black fugitive emissions were underestimated at all opacity levels. Opacity was lower on average by 5% opacity at the 15% opacity level and by 11% opacity at the 40% opacity level. It was also observed that for both white and black simulated fugitive emission plumes, the observers sensitivity to changes in opacity levels declined relative to the conventional vertical stack plumes.

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CONTENTS

Abstract iii

Figures vi

Tables vi

Acknowledgements vii

1 Introduction 1

2 Conclusions and Recommendations 2

3 Experimental Design 3
- Test Location 3
- Smoke Generators 3
- Observers 3
- Observer Tests 4

4 Data Acquisition and Quality Assurance 7
- Generator Calibration 7
- Generator Calibration Error 7
- Generator Zero and Span Drift 7
- Neutral-Density Filter Specifications 7
- Strip Chart Data Record 10
- Confidence Intervals-Generator Calibration and Operation 10
- Observers 10
- Documentation 10
- Tests-Plume Configuration 11
- Obscuring Mechanism 11

5 Results 12

References 18

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FIGURES

Number		Page
1	Modified smoke generator for emitting simulated fugitive emission plumes of known opacities	5
2	Conventional smoke generator for emitting verticle stack plumes of known opacities	6
3	Observer opacity evaluations versus transmissometer measured opacities of conventional vertical white smoke plumes viewed against a sky background on a clear day	13
4	Observer opacity evaluations versus transmissometer measured opacities of conventional vertical black smoke plumes viewed against a sky background on a clear day	14
5	Observer opacity evaluations versus transmissometer measured opacities of simulated white fugitive plumes viewed against a terrestrial background on a clear day	16
6	Observer opacity evaluations versus transmissometer measured opacities of simulated black fugitive plumes viewed against a terrestrial background on a clear day	17

TABLES

1	Conventional Smoke Transmissometer Calibration Data	8
2	Simulated Fugitive Smoke Transmissometer Calibration Data	9
3	Test Conditions	12

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SECTION 1

INTRODUCTION

Many types of airborne particles and aerosols are not emitted from conventional vertical stacks. Instead, these emissions may come from windows, roof monitors, vents, conveyor belts, hoppers, storage piles, construction sites, roads, and a variety of other sources. Often these unconfined emissions originate close to the ground and move with the wind in a horizontal direction; however, unlike conventional smokestack plumes that are viewed against the sky, these emissions are usually viewed against a darker terrestrial background. Researchers such as Conner (1,2), Himil (3), and Hood (4) have long recognized that the contrast betwen the plume and the backgrouind have an effect on the opacity assigned by observers to the emissions. The introduction to EPA Revised Method 9 states: "Studies of the theory of opacity and field studies have demonstrated that a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background (5)." Atmospheric visibility studies have reached the same conclusions and even in nature it is well known that the background matching ability of chameleons reduce their visibility.

This study was designed to determine the biases, if any, introduced when a certified Method 9 smoke reader assigns opacity values to ground-level emissions viewed against non-sky backgrounds.

A conventional smoke generator, used in the training and certification of trained visible emission (VE) observers, was modified to emit smoke plumes horizontally below the eye level of the observers, who then viewed the smoke plumes against a terrestrial background. To determine that the observers selected for the panel were capable of making unbiased opacity readings of vertical-flow stack plumes under good viewing conditions, an unmodified generator was used to produce vetical plumes for evaluation at the same time.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The study indicated that the panel of smoke readers evaluated the opacities of simulated white (horizontal-flow) fugitive emissions with accuracies similar to the (vertical-flow) stack plume opacity measurements when opacity levels were around 15 - 20%. As opacity levels increased, however, the panel increasingly underestimated them; opacity was lower on average by about 8% opacity at the 40% opacity level.

Black (horizontal-flow) fugitive emissions were underestimated at all opacity levels. At 15% opacity, the observers measured the emissions 5% opacity low; at 40% opacity, they measured them 11% opacity low. Overall, the observer panel's sensitivity to opacity changes was less for simulated (horizontal-flow) fugitive emissions than for conventional (vertical-flow) stack plumes. The change in panel opacity measurement per change in transmissometer opacity measurement declined from near 1.00 for stack plumes to 0.62 and 0.77 for white and black fugitive plumes, respectively.

It is recommended that controlled tests of observer and transmissometer opacity measurements of simulated black and white fugitive emissions be conducted for other environmental lighting conditions, e.g., on an overcast day. It is also recommended that a lower opacity level around 5 or 10% be included in the tests.

SECTION 3

EXPERIMENTAL DESIGN

TEST LOCATION

The field tests were conducted at a location in Raleigh, North Carolina where the topography of the site was well suited for the study. An embankment allowed the readers to be located above the fugitive smoke generator where they viewed the plumes against a terrestrial (vegetation) background. For the conventional vertical stack plume simulation the other generator was used and the observers moved down the embankment where their view was more representative of normal stack plumes with a sky background.

SMOKE GENERATORS

Two smoke generators were utilzied during each field test. The generators were commercially available units that are commonly used at visible emission training schools. Both generators meet the EPA specifications for Method 9 training and certification as specified in the Federal Register (5).

One generator was modified to emit a horizontal plume near ground level. The modification was achieved by leaving the stack in the horizontal (stored) position and installing a 90° elbow between the lower vertical section of the stack and the upper horizontal section of the stack. The elbow was caulked and shimmed to prevent leaks. This method of generating a horizontal plume was selected after stratification tests showed that the smoke remains uniformly dispersed in both vertical and horizontal axes near the duct exit (where a transmissometer was located) and in the stack exit plumes. The stratification tests consisted of viewing a white plume against a black velvet background at close range, and viewing a black plume against a white background. The appearance of both plumes was uniform along both axes. To further simulate the fugitive nature of a horizontal fugitive plume, a panel was placed in front of the stack end in order to block the observers' direct view of the emission exit point.

The other smoke generator was set up with the stack in the normal upright position to emit vertical-flow smokestack plumes in the conventional manner.

OBSERVERS

The observers selected for the study were six inspectors from a state agency and two air pollution personnel from local contractors. Each participant possessed a current Method 9 certification and a past

record of accurate smoke reading, as evidenced by his ability to certify promptly at a smoke school. The Method 9 certification procedure is described in the Federal Register (6). The participants ranged in age from 26 to 38 years old with an average age of 31. Three possessed college degrees, three had associate degrees and the other two had some education beyond high school. Their experience at reading visible emissions ranges from one to eight years, with an average of 4.1 years.

Since the test session was relatively long, observer fatigue was of concern. The general concensus of the observers, however, was that no fatigue problem was apparent despite the fact that they were required to read emissions for six hours, three in the morning and three in the afternoon.

OBSERVER TESTS

Both black and white simulated (horizontal-flow) fugitive emissions and (vertical-flow) stack plumes were tested under clear sky conditions. The vertical-flow plumes were tested to confirm that the observers were able to assign unbiased opacity values to conventional stack plumes. During each test, the observers were required to observe for 12 minutes. Within that 12-minute period, there was a period of just over six minutes of steady opacity smoke. The average of 24 consecutive readings by an observer during this six-minute period was the observers EPA Method 9 evaluation of the smoke opacity. The opacity levels selected for the study were 40%, 30%, 20%, and 15%. The observers were exposed to the same levels from each generator, but in random order. Observers were given no review of emission opacities prior to testing and were given no instructions except how to complete the field test form and to read on signal. Opacity values were recorded on computer compatible data forms in bound books. The observers were instructed to read by a prerecorded tape at 15-second intervals to assure Method 9 compatibility and standardization of the time reference. At the same time, the data logger made a reference mark on the transmissometer strip chart record.

To minimize any potential bias effects that may result from observer fatigue or change in the sun angle, the vertical generator was operated for only a few runs, then the horizontal generator was operated. This cycle was repeated throughout the six-hour test. Consequently, observers were required to shift their observation positions between those illustrated in Figures 1 and 2.

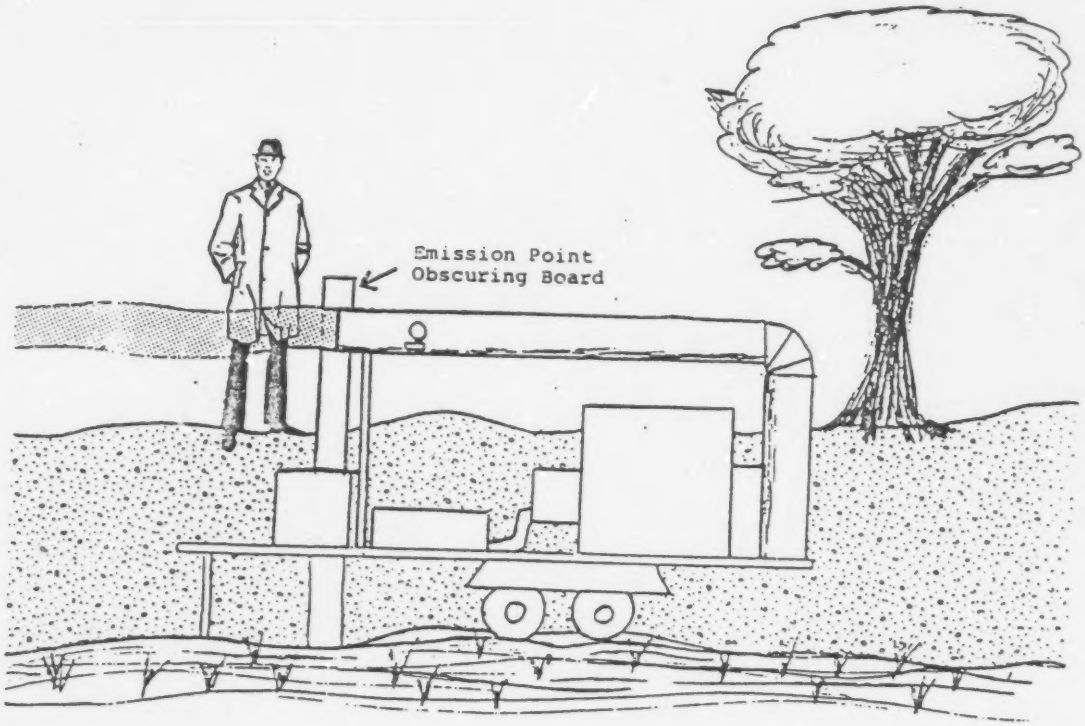

Figure 1. Modified smoke generator for emitting simulated fugitive emission plumes of known opacities.

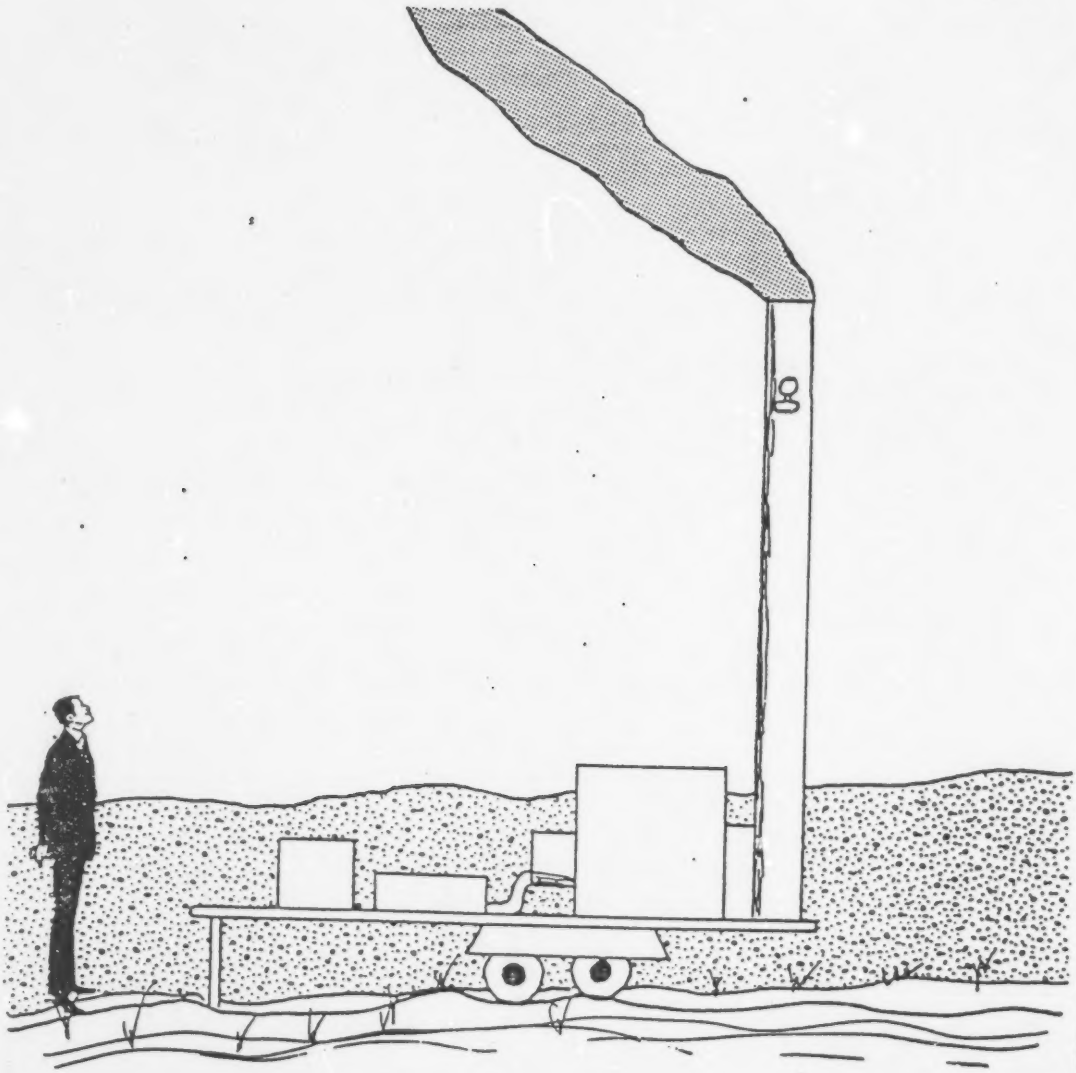

Figure 2. Conventional smoke generator for emitting verticle stack plumes of known opacities.

SECTION 4

DATA ACQUISITION AND QUALITY ASSURANCE

All transmissometer data were accumulated on a strip chart recorder operated at one inch per minute. The recorder unit was connected to the transmissometer of each of the generators during its phase of operation. In addition to the continuous strip chart trace of the opacity levels, the observation times were also marked on the charts.

Each VE observer was provided a bound book of data forms adequate to last over the test period. The forms were designed for ease in data reduction and to provide information on the test type, test number, position of the observer in relation to the sun, and the viewing conditions.

GENERATOR CALIBRATION

Both generators were span calibrated after allowing a minimum of 30 minutes warmup by alternately producing simulated opacities of 0% and 100%. The stable 0% and 100% opacity values of each generator were verified by alternately switching the power to the light source on and off while the smoke generator was not producing smoke. This procedure was performed prior to conducting the laboratory calibration error tests described below, and the actual field session of the fugitive emissions study.

GENERATOR CALIBRATION ERROR

The error between the actual response and the theoretical linear response of the smoke meter was measured by inserting a series of three NBS traceable neutral-density filters of nominal opacity of 20, 50, and 75% in the smoke meter pathlength. The calibration error for the transmissometer in each generator was determined by the filter insertion procedure described in the Federal Register (5). The calibration results are shown in Tables 1 and 2.

GENERATOR TRANSMISSOMETER ZERO AND SPAN DRIFT

Zero and span checks of the transmissometers were performed periodically to measure the amount of opacity drift from the generators. This procedure was conducted at the end of every two tests.

NEUTRAL-DENSITY FLTER SPECIFICATIONS

National Bureau of Standards (NBS) traceable neutral-density filters of nominal opacity of 20, 50, and 75% were used to calibrate the smoke generators. These filters were calibrated within $\pm$ 2%.

TABLE 1. CONVENTIONAL SMOKE TRANSMISSOMETER FILTER CALIBRATION DATA

Reading Number	Transmissometer Reading	Filter Value
1	72	73
2	22	23.5
3	46	47
4	72	73
5	22	23.5
6	46	47
7	72	73
8	22.5	23.5
9	46	47
10	72	73
11	21.5	23.5
12	46	47
13	72	73
14	21.5	23.5
15	46	47
16	23.5	23.5
17	46.5	47
18	72.5	73

TABLE 2. SIMULATED FUGITIVE SMOKE TRANSMISSOMETER FILTER CALIBRATION DATA

Reading Number	Transmissometer Reading	Filter Value
1	80.5	80
2	52	52
3	18.5	19
4	80.5	80
5	52	52
6	18.5	19
7	80.5	80
8	52.5	52
9	20	19
10	80.5	80
11	52	52
12	18.5	19
13	80.5	80
14	52	52
15	19	19
16	21.5	19
17	53	52
18	80.5	80

STRIP CHART DATA RECORD

Each test was recorded on strip chart paper by a continuous trace of the opacity and listing the following information: * - start point, + - stop point, test number, test type, each reading number and point at which a reading was made. Calibration error checks included filter value - percent opacity, measured value - percent opacity, calibrated by, date of calibration, location, generator, and filter set number.

CONFIDENCE INTERVALS - GENERATOR CALIBRATION AND OPERATION

Statistical analysis was conducted to determine the 95% confidence interval. Information necessary for this evaluation were (1) filter calibration error (from manufacturer), (2) filter calibration error check (actual filter value vs measured filter value), (3) plume configuration tests - one test for each of the four levels was verified for each study. The quality assurance coordinator recorded the 48 readings per test from the strip chart. An auditor independently read the same 48 readings per test from the strip chart for data validation and reduction purposes.

OBSERVERS

Qualified observers meeting the specifications of Federal Reference Method 9 were utilized as visible emissions evaluators. Meeting Method 9 specifications means that each observer's maximum average deviation on white and black smoke did not exceed 7.5% opacity and no single error exceeded 15% opacity during their certification test. The participants were instructed prior to each study not to discuss their readings for the tests. The observers were not shown any plumes for reference opacities on the days of the studies. Eight readers participated in the study.

DOCUMENTATION

Strip Chart Data

Calibration error, strip charts for each test, and strip chart data forms were kept on a bound book. Each data form includes a test type, test number, participant number, reader position, background conditions, 48 fifteen-second interval readings, and strip chart data reduction (person and date).

Participant Data

Each reader received a bound book containing a participant data form (individual's background information), field test coding form, and field test data forms. Each field test data form includes the following: test type, test number, participant number, reader position, background conditions, 48 fifteen-second interval readings, and the participant's signature.

Generator Operator Log

A generator data form, comments sheet, and plume configuration curves for all tests were in bound book format to assist the generator operator in providing accurate opacity levels for the tests. The generator data form includes a test number, test type, flat trace opacity percent, time period for flat trace opacity, generator operator, generator type - ETA for horizontal or EPA for vertical, time of test, recorder chart speet, and comments.

TEST-PLUME CONFIGURATIONS

Emissions were generated at four different opacity levels. The levels were selected at random by die tossing. Each test was conducted over a 12-minute period (48 readings at 15-second intervals). The timing of the test and reading intervals were verified by stopwatches. During this time period, a six-minute period for the selected flat trace opacity was generated for the required 24 readings at 15-second intervals. Flat trace opacity percent levels for both black and white smoke were (1) 15%, (2) 20%, (3) 30%, and (4) 40%.

OBSCURING MECHANISM

An obscuring mechanism (plywood board) was used to prevent the readers from directly viewing the emission point from the horizontal stack of the generator. This was done to make the plume more analogous to a fugitive plume.

SECTION 5

RESULTS

To observe the effect each smoke color and mode of emission had upon the observers when they evaluated fugitive emissions, observer results were plotted against actual transmissometer values. All tests were conducted on a clear day between 9 AM and 3 PM.

Table 3 presents a matrix of the test conditions and a list of the corresponding figures where the data are shown.

TABLE 3. TEST CONDITIONS

Plume Configuration	Smoke Color	Background	Figure
Conventional stack plume	White	Clear Sky	3
Conventional stack plume	Black	Clear Sky	4
Simulated fugitive plume	White	Dark terrestrial	5
Simulated fugitive plume	Black	Dark terrestrial	6

The test results of VE observer measurements of (vertical-flow) stack plumes under blue sky conditions (Figures 3 and 4 for white and black plumes, respectively) show that panel (averaged observer) opacity measurements and their regression lines were close to the 1 to 1 line of agreement with the smoke generator transmissometer opacity measurements over the range of opacities used in the study. Slopes of 1.17 and 1.01 were observed. The between-observer variation of the data as evidenced by the confidence intervals of the means was more than expected and previously observed for the method (2,3). The reason for this increased variation was not investigated but may have been due to the procedure of alternating the observers betwen the smoke generators during the test. The between-observer variation is not the focus of this study. It is the panel (averaged observer) opacity readings when viewing the conventional and simulated fugitive plumes that are compared to determine any bias in Method 9 trained VE observers when evaluating fugitive plumes.

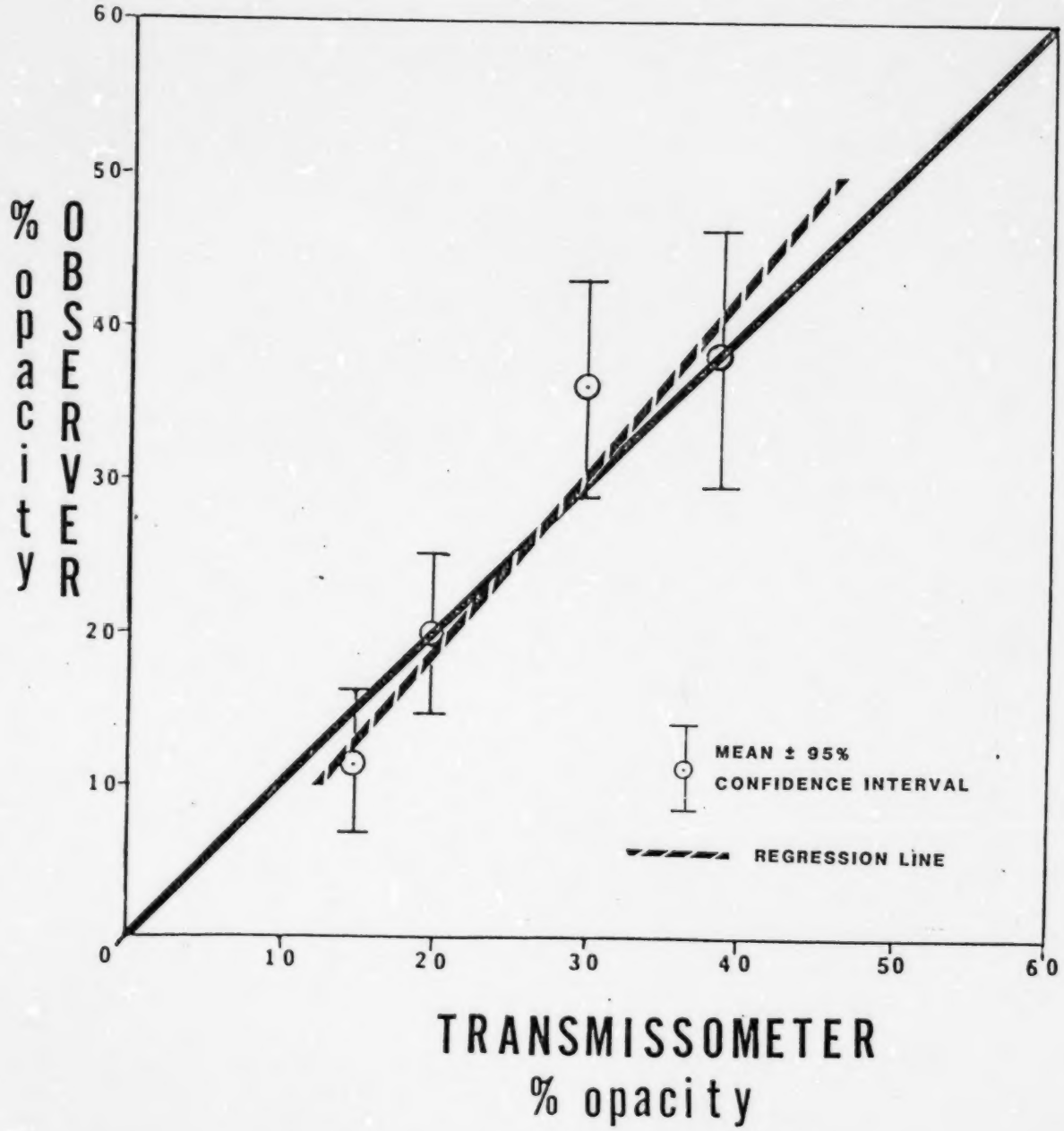

Figure 3. Observer opacity evaluations versus transmissometer measured opacities of conventional vertical white smoke plumes viewed against a sky background on a clear day.

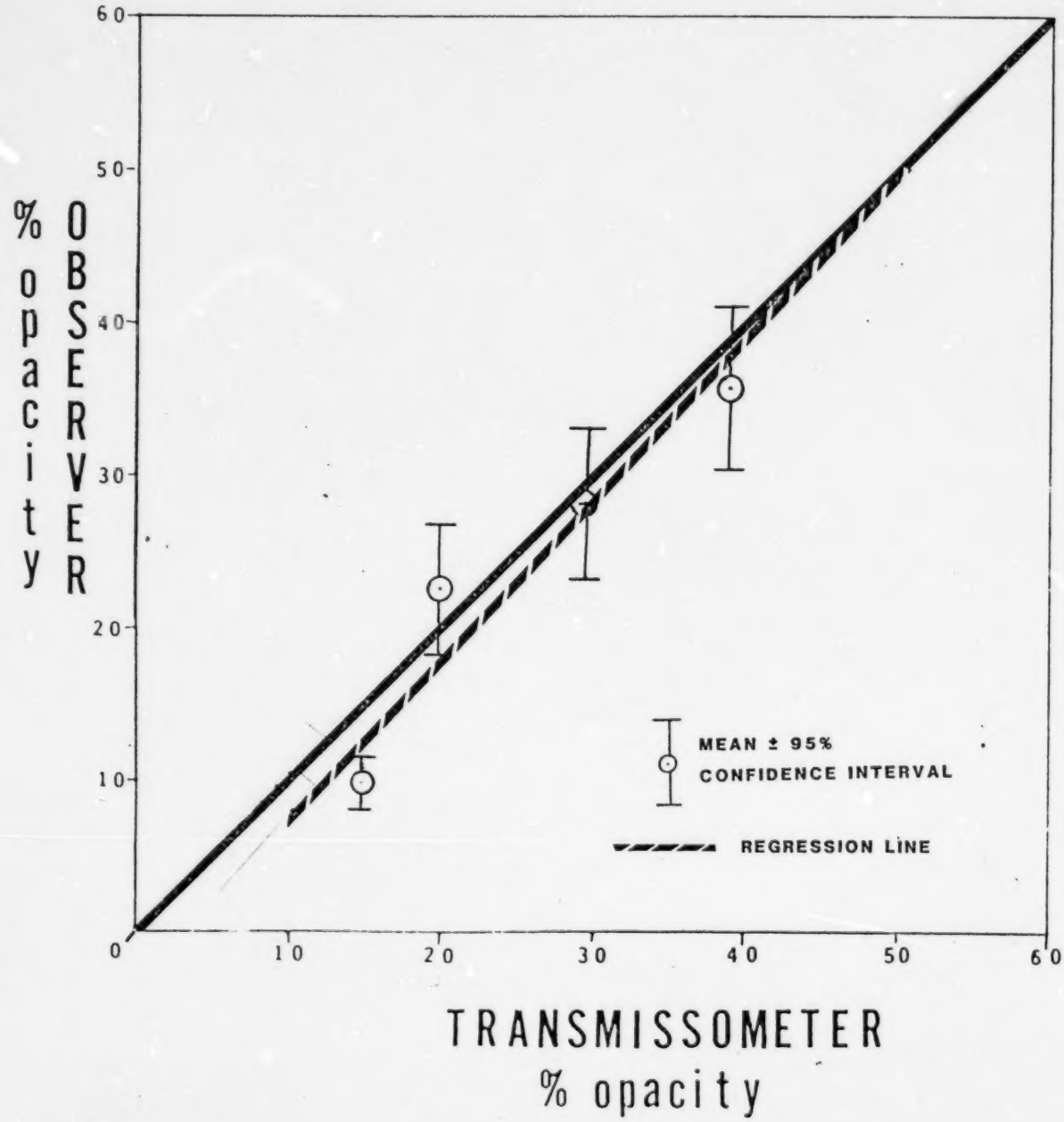

Figure 4. Observer opacity evaluations versus transmissometer measured opacities of conventional vertical black smoke plumes viewed against a sky background on a clear day.

The simulated fugitive emissions test results for white plumes on a clear day (Figure 5) indicate no systematic difference (bias) between observers and transmissometer values for opacities around 15 - 20%. At higher opacities Figure 5 indicates an increasing negative observer bias. At 40% opacity, this bias resulted in observer panel readings around 8% opacity lower than the transmissometer values. The black simulated fugitive emissions test results (Figure 6) indicate lower observer panel values at all opacity levels. At 15% opacity they were 5% opacity low, and at 40% opacity they were 11% opacity lower than the transmissometer values. The data also indicate that the observer sensitivity to opacity changes, as evidenced by the slopes of the curves, declined for both the white and black fugitive emission plumes. The change in observer measured opacities per change in transmissometer measured opacities declined from near 1.0 for the conventional verticle stack plume measurements to 0.62 and 0.77 for the white and black simulated fugitive plume measurements.

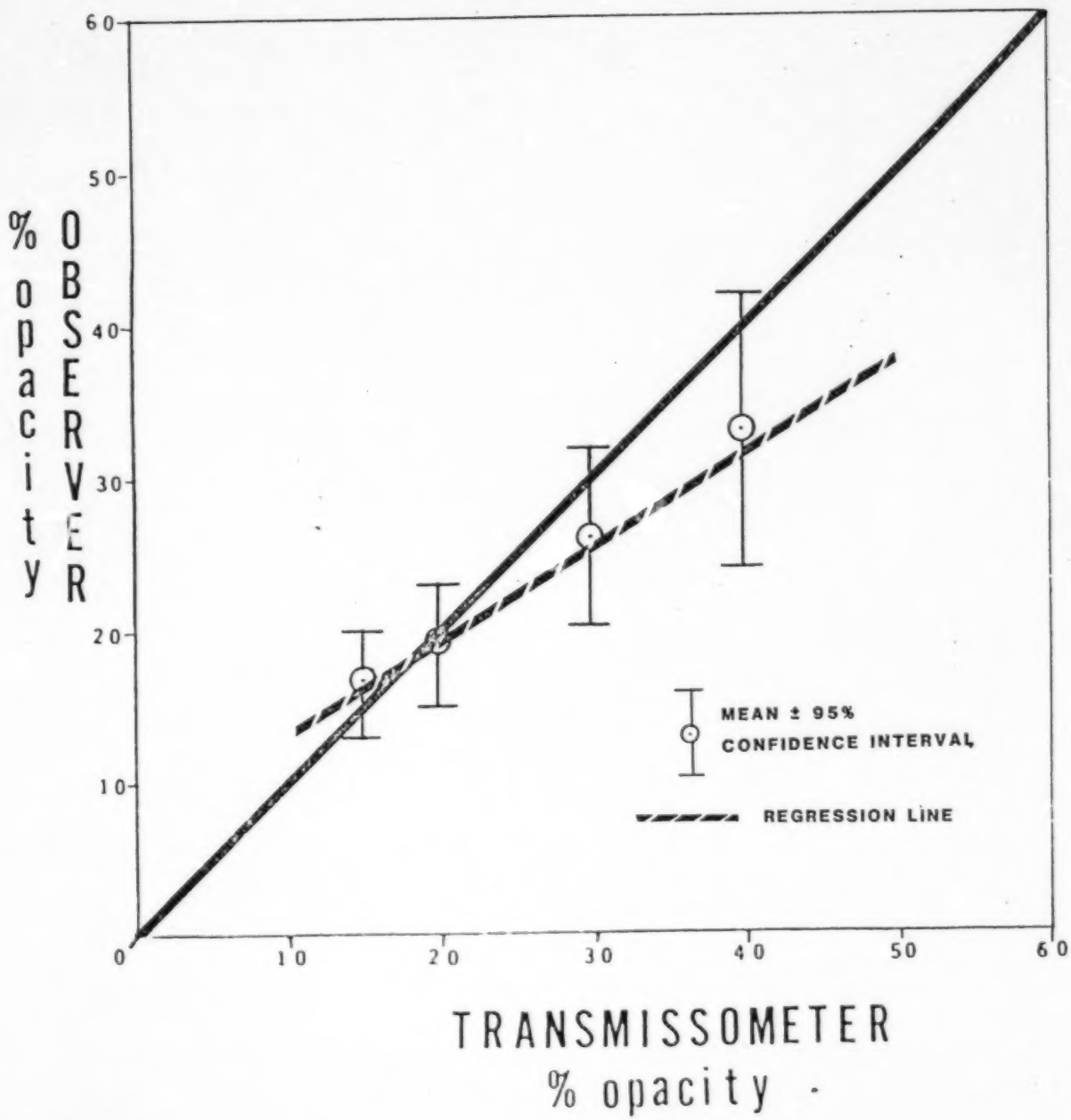

Figure 5. Observer opacity evaluations versus transmissometer measured opacities of simulated white fugitive plumes viewed against a terrestrial background on a clear day.

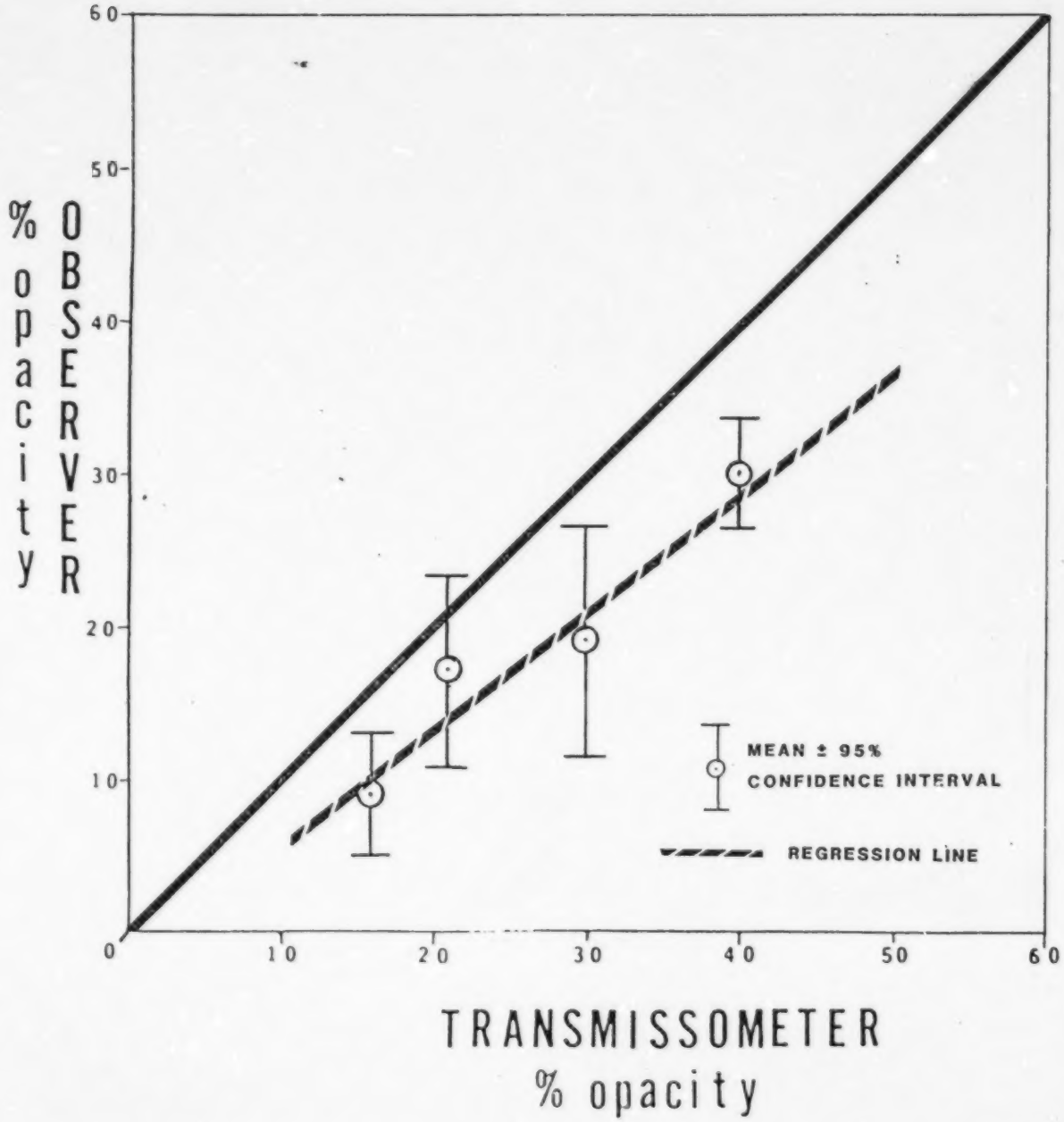

Figure 6. Observer opacity evaluations versus transmissometer measured opacities of simulated black fugitive plumes viewed against a terrestrial background on a clear day.

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